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The work performed in the reporting period has been focused on continuation of Task 1.1, early part of Task 1.2 and Task 2.2 described in the project proposal. The activities related to Task 1.1 are formation of cracks in a computational micromechanics failure analysis of a representative volume element containing disordered fiber distributions. As a preamble to Task 1.2, procedures have been developed to introduce the initiated cracks and to analyze their growth and instability in the environment of the disordered fiber distributions. The activities related to Task 2 cover the new peridynamic model for multi-phase composites which can introduce the presence of pores and manufacturing defects in the intermediately-homogenized model of fiber-reinforced composites.

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Quarterly Progress Report, January 1 – March 31, 2017

A Hybrid Approach to Composite Damage and Failure Analysis Combining Synergistic Damage Mechanics and Peridynamics

Award Number N00014-16-1-2173

DOD – NAVY – Office of Naval Research

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Executive Summary

The work performed in the reporting period has been focused on continuation of Task 1.1, early part of Task 1.2 and Task 2.2 described in the project proposal. The activities related to Task 1.1 are formation of cracks in a computational micromechanics failure analysis of a representative volume element containing disordered fiber distributions. As a preamble to Task 1.2, procedures have been developed to introduce the initiated cracks and to analyze their growth and instability in the environment of the disordered fiber distributions. The activities related to Task 2 cover the new peridynamic model for multi-phase composites which can introduce the presence of pores and manufacturing defects in the intermediately-homogenized model of fiber-reinforced composites.

Task 1.1 Micro-level crack initiation

Background and motivation

In most manufacturing processes for polymer matrix composites (PMCs) one starts with dry bundles of fibers. On resin infusion, the initially closed-pack fibers are spread out to the extent dictated by the intended fiber volume fraction. Whether the end product is a pre-impregnated layer, or a thick part produced by resin transfer molding (RTM), the configuration in which the fibers finally appear is far from uniform. The final nonuniform distribution of fibers consists of clustered fiber regions and resin pockets. The initiation of failure due to fiber clustering was reported in the Fourth Quarterly Report for the period October 1 – December 31, 2016. In this reporting period, the work is continued to examine formation of cracks from the point failures. Further growth of the formed cracks will be continued as proposed in Task 1.2 Ply Level Constrained Cracking.

Approach and Results

As reported in the last Quarterly Report, the results of the failure analysis of a representative volume element (RVE) simulating a sample of the composite showed that for a given fiber volume fraction in a composite, a more clustered region of fibers (i.e. for smaller range of variation of the radial distance r), initiated debonding earlier (at lower applied strain). As was reported there, the smallest radial displacement of fibers in the range ±0.5r produced failures at the lowest applied strains, while at the largest radial variation range, ±0.5r, not all realizations produced dilatation induced debonding, and a higher strain had to be applied to get debonding in the realizations that showed this failure. The rotational movement of the fibers during processing was kept in the range of ±15 degrees from the initial position in the fiber bundle.

In the previous report, the effect of microvoids that occupy spaces between fibers and are not removed during the manufacturing process was also reported. It was found that as the void size is increased, the presence of voids affects (increases) the debonding strain. At the void size of 5.0 μm one out of five realization was affected, while two out of five realizations had increased debonding strain for 10.0 μm voids. It was found that for ±0.4r, smaller voids that are able to find their way into the spaces between fibers reduce the tendency for debonding, while larger voids that get into the resin pockets have smaller effect on debonding.

To continue the failure analysis toward formation of microcracks, the RVE with ±0.4r and ±15 degrees is considered. A total of four realizations of the RVE were constructed. Figure 1 shows one of the realizations for illustration indicating first occurrence of cavitation.

Figure 1. One realization of the RVE with disordered fiber distribution showing as a red dot the point where the first initiation of cavitation occurs under transverse tension.

On increasing the applied load (measured in strain in the horizontal direction), more points suffer cavitation. Figure 2 shows all points of cavitation at the applied strain of 0.5%. As seen in the figure, the cavitation points tend to cluster in the region where the interfiber distances are relatively small. On coalescence of the cavitation cluster (via fiber-matrix debonding) a short transverse crack forms.

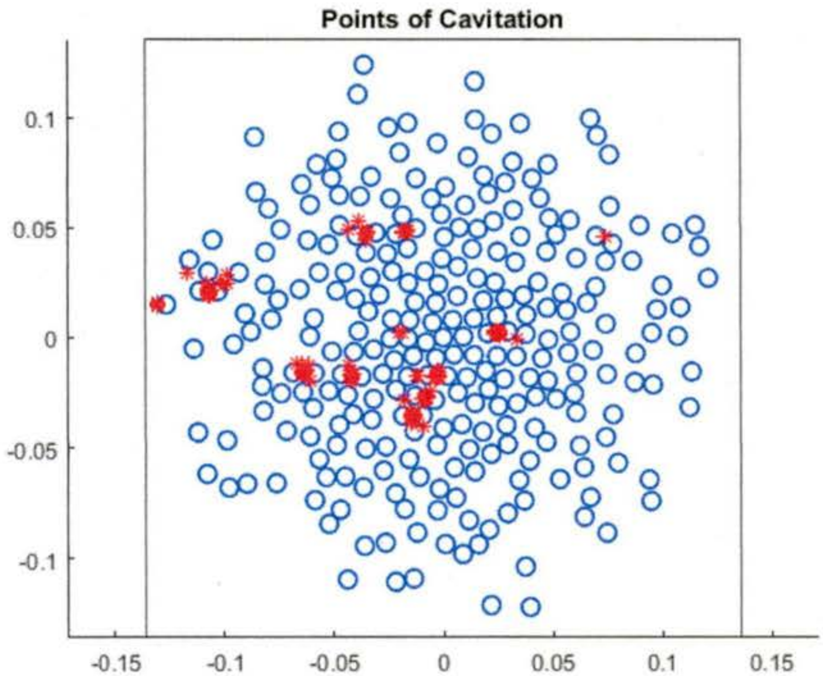

Figure 2. Points of cavitation within the RVE at applied strain of 0.5%. The cluster of cavitation points tend to form a crack with its plane normal to the applied tensile load.

Figure 3 shows further progression of damage subsequent to the microcrack formation. As seen there, more cavitation occurs ahead of the crack tip. As a consequence of the fiber distribution disorder, the upper crack tip induces more cavitation than the lower crack tip. The unsymmetric growth of the microcrack predicted here is in agreement with numerous experimental observations. It is noted that the unsymmetric crack growth cannot be predicted by models that homogenize the composite, as done in most damage models in the literature.

It is also found that on loading the composite with an inserted crack, as depicted in Fig. 3, further cavitation occurs at a strain earlier than the strain at which the band of cavitation occurred that formed the crack. This suggests that the crack growth is a brittle (unstable) process, again as evidenced by experimental observations.

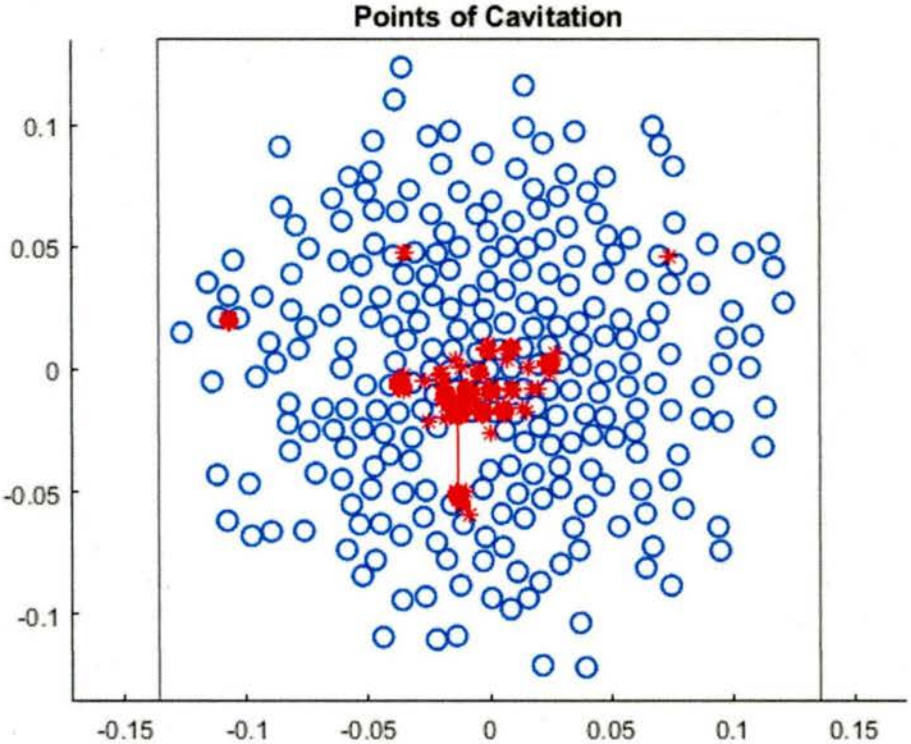

Figure 3. Cavitation ahead of the crack tips. Note that the upper crack tip induces more cavitation than the lower tip.

Table 1 summarizes the results for four RVE realizations. Note that the strain for cavitation after crack formation is lower than that for cavitation before crack formation.

Realization	Strain @ Cavitation before crack	Strain @ Cavitation After cracking
1	0.005	0.004
2	0.005	0.004
3	0.004	0.002
4	0.004	0.002
Avg	0.0045	0.003

Table 1. The applied mechanical strain (added to the thermal cooldown) at which cavitation occurs in the four realizations of the RVE before and after microcrack formation.

The ongoing research will focus on effects of matrix voids on cavitation induced cracking and on cracking under the constraint of neighboring plies.

Task 2 Peridynamic model for FRCs based on a multiple-phase composite model

Background and motivation

Manufacturing defects, like voids/pores in the matrix and weak planes at the matrix-fiber interfaces, make the material softer and weaker. Implementing such initial damage into the computational model is critical for predicting the performance and the failure mode of the fiber-reinforced composite (FRCs). Previously, we introduced a new Intermediate Homogenization Peridynamic approach (IH-PD model) for failure in multiphase materials. We plan to apply this IH-PD model for the implementing of initial damage (provided by the SDM approach, see previous sections) and modeling of crack growth and coalescence, through full failure of FRCs.

Approach and Results

Different from the Locally-Homogenized approach (LH-PD model), in which the properties of a PD bond are computed locally based on a classically homogenized composite material, in the IH-PD model we assume two types of bonds in a two-phase composite: inter-phase and intra-phase bonds, which represent the properties of the distinct composite phases and of interfaces between them. This model is directly extendable to multiple-phases.

The fully homogenized LH-PD model, due to ignoring of all microstructural details, cannot differentiate types of initial damage. In the new IH-PD model, the initial voids in the matrix can be simulated by introducing pre-damage in the matrix intra-phase bonds, while weak planes at the matrix-fiber interfaces can be implemented by weakening or pre-damaging some of the matrix-fiber inter-phase bonds. The distribution of different bonds in the IH-PD model depends on the volume fraction of the phases at the locations where the ends of the bond reside (see Fig. 2.1). Because of this extra information about the microstructure, the model is capable of capturing failure caused by the existence of pores or defects in the material.

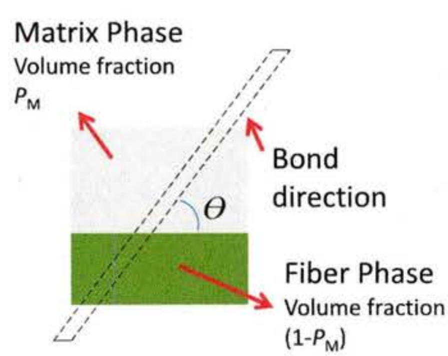

Fig. 2.1 Schematic for the new PD model with intermediate homogenization (IH-PD) for modeling FRCs. The PD bond-type depends on the relative direction between the bond

direction and the fiber direction, and the matrix-fiber bond properties are related to the volume ratio between the matrix phase and the fiber phase.

In this quarter, we have tested the new IH-PD model against existing experimental results for fracture in a Functional Graded Material (FGM) plate. In this case, the matrix was epoxy, and the inclusions small glass spheres. The volume fraction of glass spheres varies, gradually, from one side of the plate to the other, creating the FGM. Because, in this case, the distribution of inclusions has no preferred orientation, the FGM material is locally isotropic. The distribution of different bonds in the IH-PD model only depends on the volume fraction of the phases in the nodes. The results from this work have been submitted for publication as a book chapter (see [1]) in a new *Handbook of Nonlocal Continuum Mechanics for Materials and Structures*, edited by George Z. Voyiadjis (LSU), and a journal paper (see [2]).

In the next quarter, we will implement and test the new IH-PD model for *anisotropic* multiphase material, such as FRCs. We have obtained some preliminary results with this model that are very encouraging. Figure 2.2 shows the distributions of horizontal direction displacements in a unidirectional FRC under horizontal tensile loading. The IH-PD model correctly predicts the displacement distribution in the lamina plate for different fiber directions.

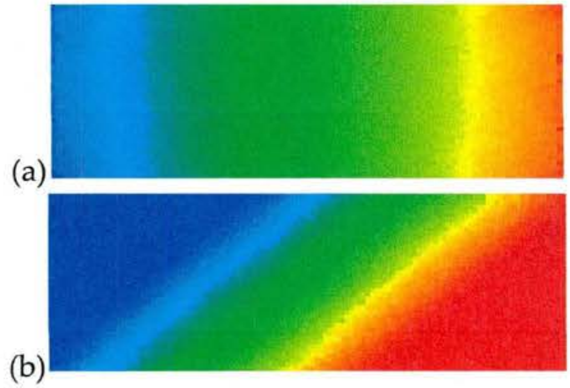

Fig. 2.2 Distributions of horizontal displacements for laminas under horizontal loadings, with different fiber orientations: 0^{o} (top), and 45^{o} (bottom).

Following calibration and further testing for the elastic behavior, we will perform fracture studies with different levels of pores and manufacturing defects.

Publications

[1] Z. Chen, S. Niazi, G. Zhang, and F. Bobaru. "Peridynamic Functionally Graded and Porous Materials: Modeling Fracture and Damage", submitted for publication as a chapter in *Handbook of Nonlocal Continuum Mechanics for Materials and Structures*, George Z. Voyiadjis (ed.), 2017.

[2] Z. Chen, S. Niazi, G. Zhang, F. Bobaru. "An intermediate homogenization approach for fracture in multiphase composites", to be submitted, (2017).